

Topical Report
for
March 2003 to March 2004

by
Precision Combustion, Inc.
410 Sackett Point Road
North Haven, CT 06473

under
DOE Contract DE-FC26-03NT41721
"Ultra Low NO_x Catalytic Combustion for IGCC Power Plants"

March 2004
Dr. Lance L. Smith

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Abstract

Tests were performed in PCI's sub-scale high-pressure (10 atm) test rig, using PCI's two-stage (catalytic / gas-phase) combustion process for syngas fuel. In this process, the first stage is a Rich-Catalytic Lean-burn (RCLTM) catalytic reactor, wherein a fuel-rich mixture contacts the catalyst and reacts while final and excess combustion air cool the catalyst. The second stage is a gas-phase combustor, wherein the catalyst cooling air mixes with the catalytic reactor effluent to provide for final gas-phase burnout and dilution to fuel-lean combustion products.

During the reporting period, PCI successfully achieved $\text{NO}_x = 0.011 \text{ lbs/MMBtu}$ at 10 atm pressure (corresponding to 2.0 ppm NO_x corrected to 15% O_2 dry) with near-zero CO emissions, surpassing the project goal of $< 0.03 \text{ lbs/MMBtu NO}_x$. These emissions levels were achieved at scaled (10 atm, sub-scale) baseload conditions corresponding to Tampa Electric's Polk Power Station operation on 100% syngas (no co-firing of natural gas).

Table of Contents

Title Page	1
Disclaimer.....	2
Abstract	3
Table of Contents	4
Executive Summary.....	5
1. Introduction.....	6
2. Preliminary Work: Atmospheric Pressure Tests and Numerical Modeling	7
3. High-Pressure (10 Atm) Test Hardware and Experimental Setup	12
4. Basis for High-Pressure Test Conditions	14
5. High-Pressure Sub-Scale Test Results for Syngas Fuel.....	17
6. Phase I Summary and Recommendations	22
7. Assessment of Potential Success and Feasibility for IGCC.....	22

Executive Summary

This Topical Report describes the Phase I results obtained for catalytic combustion of syngas fuel, under PCI's contract with DOE. The current project was awarded following proposal submission by PCI, in response to DOE solicitation DE-PS26-02NT41422-5 Area of Interest 5. The technology to be developed uses the fuel flexibility of PCI's Rich-Catalytic Lean-burn (RCLTM) catalytic reactor in a combustion system for syngas fuel.

Funding was received through the U.S. DOE Fossil Energy's Innovation for Existing Plants program, to develop technologies that further reduce the low NO_x emissions resulting from the two existing IGCC facilities in the U.S. Additionally, this technology targets meeting DOE's Vision 21 target of NO_x emissions < 0.01 lbs/MMBtu (< 3 ppm @ 15% O₂) for coal-derived fuels. The technology offers these low emissions without the cost of exhaust after-treatment, with high efficiency (avoidance of after-treatment losses, and reduced diluent requirements), and with catalytically stabilized combustion which extends the lower Btu limit for syngas operation.

During the reporting period, Phase I milestones were achieved and the NO_x emissions project goal of less than 0.03 lbs/MMBtu was met. NO_x emissions were generally near 0.01 lbs/MMBtu (our target) and were below this value under some operating conditions during parametric testing.

Tests were performed in PCI's sub-scale high-pressure (10 atm) test rig, using PCI's two-stage (catalytic / gas-phase) combustion process for syngas fuel. In this process, the first stage is a Rich-Catalytic Lean-burn (RCLTM) catalytic reactor, wherein a fuel-rich mixture contacts the catalyst and reacts while final and excess combustion air cool the catalyst. The second stage is a gas-phase combustor, wherein the catalyst cooling air mixes with the catalytic reactor effluent to provide for final gas-phase burnout and dilution to fuel-lean combustion products.

Phase I milestones and corresponding accomplishments are listed here, showing that the milestones were met successfully:

- **Milestone 1: Successful high-pressure catalytic combustion of syngas.** Tests were performed in PCI's sub-scale combustion rig at 10 atm pressure with heated syngas over the planned range of operating conditions. Catalyst performance measures showed good operation (catalyst temperatures, catalytic conversion), confirming that PCI's basic reactor design, catalysts, and substrate metallurgy are applicable to syngas operation.
- **Milestone 2: Successfully achieved NO_x = 0.011 lbs/MMBtu** at 10 atm pressure (corresponding to 2.0 ppm NO_x corrected to 15% O₂ dry) with near-zero CO emissions, surpassing our project goal of < 0.03 lbs/MMBtu NO_x. These emissions levels were achieved at scaled (10 atm, sub-scale) baseload conditions corresponding to Tampa Electric's Polk Power Station operation on 100% syngas (no co-firing of natural gas).

Finally, the Phase I results were presented to the participating gas turbine OEM and a modified Phase II plan was developed in response to OEM interest. The OEM will participate in the modified Phase II work including further technology development and a detailed design study, and full-scale combustor trial following successful outcome of the detailed design study, directed toward readiness for integration in an existing gas turbine product for IGCC applications.

1. Introduction

Precision Combustion, Inc. (PCI) is testing a new method of catalytically combusting syngas fuels for ultra low emissions, with a milestone goal of achieving NO_x emissions below 0.03 lbs/MMBtu. We are targeting to be as low as 0.01 lbs/MMBtu, equivalent to < 3 ppm NO_x at 15% excess oxygen.

Currently, NO_x emissions from conventional coal-fired power plants vary widely, from about 0.4 to 2.0 lbs/MMBtu depending on burner type. Low-NO_x coal burners can reduce these emissions by roughly half, with the lowest NO_x emissions achieved being 0.10 lbs/MMBtu with sub-bituminous coal. But ultra-low NO_x emissions, to compete with natural gas fired turbines, requires alternative combustion means or aftertreatment.

One promising approach is coal gasification, followed by combustion of the resulting syngas within a gas turbine engine. IGCC power plants have been proven to achieve high efficiency with low emissions, including NO_x emissions guarantees of less than 25 ppmv (at 15% O₂), corresponding to about 0.1 lbs/MMBtu. However, further reduction in NO_x emissions, by dilution of the fuel with inert gases, faces barriers in terms of flame stability and impact on overall cycle efficiency.

Catalytic combustion is known to improve flame stability, and can also reduce NO_x emissions without excessive use of diluent, thus maintaining cycle efficiency. Therefore, PCI has proposed under this project to test its fuel-flexible catalytic combustion system with syngas fuels, to demonstrate the feasibility of achieving ultra-low NO_x emissions in IGCC power plants. The current project was awarded following proposal submission by PCI, in response to DOE solicitation DE-PS26-02NT41422-5 Area of Interest 5.

PCI's catalytic combustion system is especially well suited for syngas fuels, since it is designed to operate robustly and with constant performance using a wide range of fuels. PCI, with DOE and gas turbine manufacturer support, initially developed its advanced catalytic combustor technology for natural gas. Originally developed under DOE's SBIR program, the natural gas technology offers simultaneous improvements in emissions, efficiency, fuel flexibility and component life and is now moving toward gas turbine field trial. The technology has retrofit potential and has demonstrated good performance with multiple hydrocarbon fuels in sub-scale tests. Under large frame turbine conditions, natural-gas-fired tests have demonstrated the robustness of the technology, as well as stable combustion with NO_x emissions as low as 2 ppm and low combustion dynamics, in a package sufficiently compact to potentially fit into existing large frame machine combustor volumes. The present project is directed toward adapting and moving the technology toward a similar level of development for syngas fuels.

Syngas-fuel tests were performed as part of the Phase I effort of this project in PCI's sub-scale high-pressure (10 atm) test rig using a variant of PCI's two-stage (catalytic / gas-phase) combustion process originally developed for natural gas. In this syngas combustion process, the first stage is a Rich-Catalytic Lean-burn (RCLTM) catalytic reactor, wherein a fuel-rich mixture contacts the catalyst and reacts while final and excess combustion air cool the catalyst. The second stage is a gas-phase combustor, wherein the catalyst cooling air mixes with the catalyst

reaction effluent to provide for final gas-phase burnout and dilution to fuel-lean combustion products.

This Topical Report describes the successful Phase I project results, and includes a revised Phase II project plan based on OEM input. In summary, the Phase I milestones were met and exceeded: NO_x emissions were measured well below 0.03 lbs/MMBtu in sub-scale 10 atm tests simulating operation of Tampa Electric's IGCC plant. NO_x emissions were generally near 0.01 lbs/MMBtu (our target) and were below this value under modified operating conditions during parametric testing. OEM interest was obtained, and a modified Phase II plan was developed to evaluate actual engine integration and performance in close cooperation with the OEM.

2. Preliminary Work: Atmospheric Pressure Tests and Numerical Modeling

Syngas-fuel tests were first performed at atmospheric pressure. These preliminary tests were intended to provide some initial experience in syngas fuel operation, and in catalyst and combustor behavior using syngas fuels. The results were used to help guide reactor design and test planning for the high-pressure tests.

Specific objectives of the initial atmospheric-pressure tests were as follows:

1. Characterize RCL catalyst lightoff and extinction temperature for syngas fuel.
2. Characterize RCL catalyst operating temperature, and axial temperature profile, for syngas fuel.
3. Measure catalyst conversions and relative reactivity (H₂ vs. CO conversion).
4. Obtain preliminary NO_x and CO emissions.
5. Establish Standard Operating Procedure (SOP) for rig operation using syngas fuel (e.g. startup, catalyst lightoff, etc.).

Initial testing was performed using a syngas fuel made from a fixed blend of gases, namely 25% H₂, 35% CO, 20% N₂, and 20% CO₂. Generally, although equivalence ratio was varied during testing, the syngas blend remained fixed.

Briefly, the following observations were made:

1. For fuel-rich conditions, syngas lightoff temperature is about 180 C, while extinction temperature is < 80 C.
2. Catalyst operating temperature and axial profile were similar to those obtained using methane fuel, confirming that PCI's basic RCLTM reactor design, catalysts, and substrate metallurgy are applicable to syngas operation.
3. At atmospheric pressure, H₂ conversion was roughly double CO conversion.
4. NO_x emissions below 2.5 ppm (corrected to 15% O₂) were measured at atmospheric pressure, for 0.5 overall equivalence ratio.
5. Startup was best accomplished by bringing the reactor to fuel-rich conditions using methane fuel, with some diluent addition to ensure proper mixing. When necessary, a small amount of H₂ was temporarily added to light off the reactor. Once the catalyst and combustor were lit and the rig was thermally stable, syngas fuel flow was ramped up while methane fuel flow

was ramped down, holding catalyst equivalence ratio approximately constant. This startup procedure was both safe and economical: it minimized the use of high-volume (costly) laboratory syngas fuel blend, and also avoided use of H₂ during transient and ignition events, where there was a concern that unburned H₂ might enter the exhaust stack and create an explosion hazard.

Configuration / Hardware

Atmospheric pressure tests were performed using a pre-existing sub-scale RCL reactor. The reactor was installed with its downstream end open to atmospheric pressure. For NO_x emissions measurements, a 1.7-inch inside-diameter pipe was located downstream of the reactor, and emissions measurements were made inside this pipe approximately 15 inches downstream, where burnout was complete.

Emissions Test Conditions and Results

Emissions measurements were obtained over a range of conditions, as tabulated in Table 2-1 below. Here, overall equivalence ratio is measured at the emissions probe, downstream of the catalyst and near the exit of the gas-phase combustor. In general, the low emissions measured show that at atmospheric pressure we easily achieved our project target of less than 3 ppm NO_x emissions (< 0.01 lbs/MMBtu NO_x).

Table 2-1. Summary of emissions measurements at atmospheric pressure.

Overall equivalence ratio	CO (ppm, 15% O ₂)	NO _x (ppm, 15% O ₂)
0.53	1.5 ppm	2.6 ppm
0.50	0.8 ppm	2.4 ppm
0.45	0.8 ppm	1.9 ppm
0.40	1.4 ppm	1.5 ppm

Gas chromatograph (GC) data were also obtained from a sample port at the catalyst exit, for the last condition shown in the above table. GC analysis showed that O₂ conversion was about 90%. H₂ conversion was about 45% and CO conversion was about 26%.

Temperature profile through the catalyst bed is shown in Figure 2-1. Tin_cool is the temperature of the inlet cooling air; Tin_cat is the inlet temperature of the fuel-rich fuel/air mixture; and Ts_X is the tube metal temperature at location X. Note that thermocouples at the number 5 and 6 locations were not functioning, but temperatures at these locations can be interpolated from the number 3, 4, 7, and 8 thermocouple data.

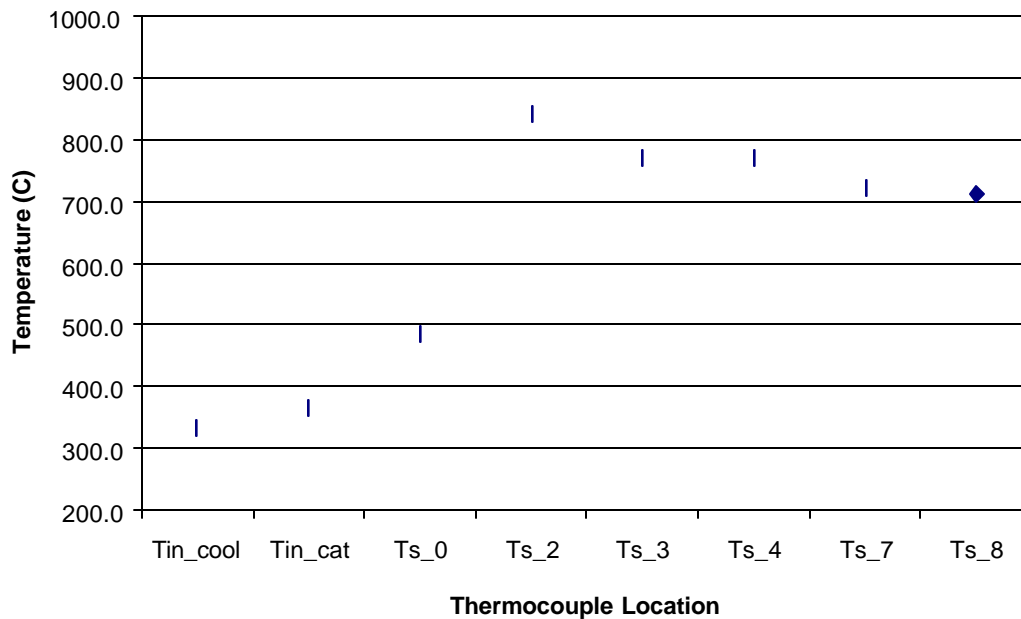


Figure 2-1. Temperature profile through the catalyst bed, for 0.5 overall equivalence ratio in the downstream combustor.

Numerical Modeling

In addition to preliminary atmospheric pressure testing, a Computational Fluid Dynamics (CFD) model of PCI's catalytic reactor was developed, and was used to predict catalyst temperature (in good agreement with the above results, as shown below) as well as catalytic conversion and heat transfer to the catalyst cooling air. The commercially-available CFD code Fluent was used, and included detailed modeling of turbulent flow, heat transfer, mass transfer of reactant and product species, and simplified chemical reaction mechanisms at the catalyst surface. Simplified chemistry was used to permit the 3-dimensional problem to become tractable and solvable in a finite period of time, using Fluent.

Predicted catalyst surface temperatures are shown in Figure 2-2 below. The prediction is in good agreement with the corresponding 1 atm test data shown in Figure 2-1, giving confidence that heat and mass transfer and reactant conversion predictions are also valid.

PCI's catalytic reactor was sized to provide the maximum heat release within material temperature limit constraints. Thus, it is desired that under fuel-rich reaction nearly 100% of the oxygen in the fuel-rich mixture is consumed by reaction with fuel. CFD calculations of oxygen conversion, the limiting process for fuel-rich reaction, are shown in Figure 2-3. Conversion of oxygen approaches 100% near the end of the catalytic reactor, as desired. Oxygen conversion and corresponding heat release through the reactor are also used to calculate heat transfer to the cooling air, as shown in Figure 2-4 (described below). At the reactor exit this heated cooling air mixes with the oxygen-depleted catalyst effluent and then burns, consuming all remaining fuel values. By burning at sufficiently low temperature, NO_x emissions are minimized.

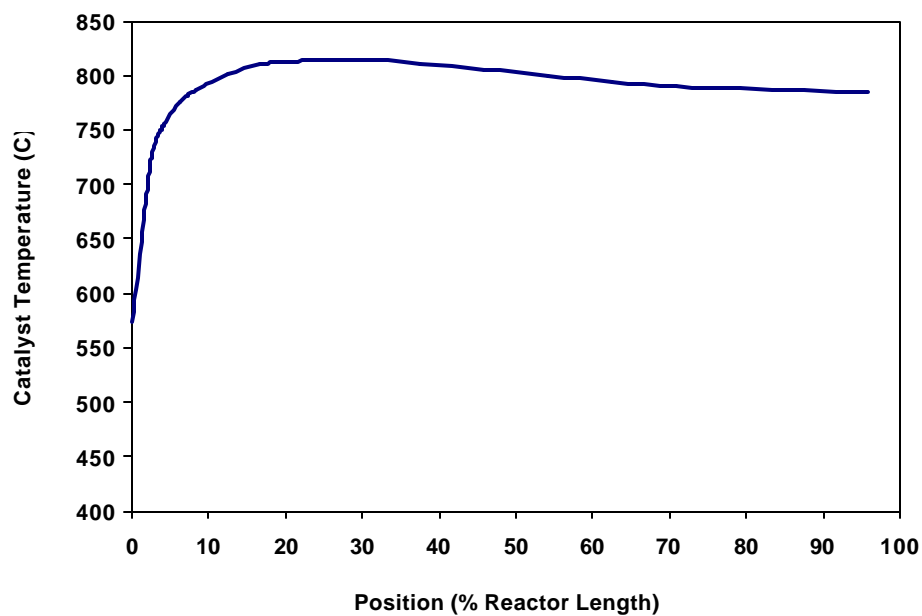


Figure 2-2. Fluent CFD predicted catalyst temperatures, as a function of length through the catalytic reactor. Note good agreement with the test data of Figure 2-1.

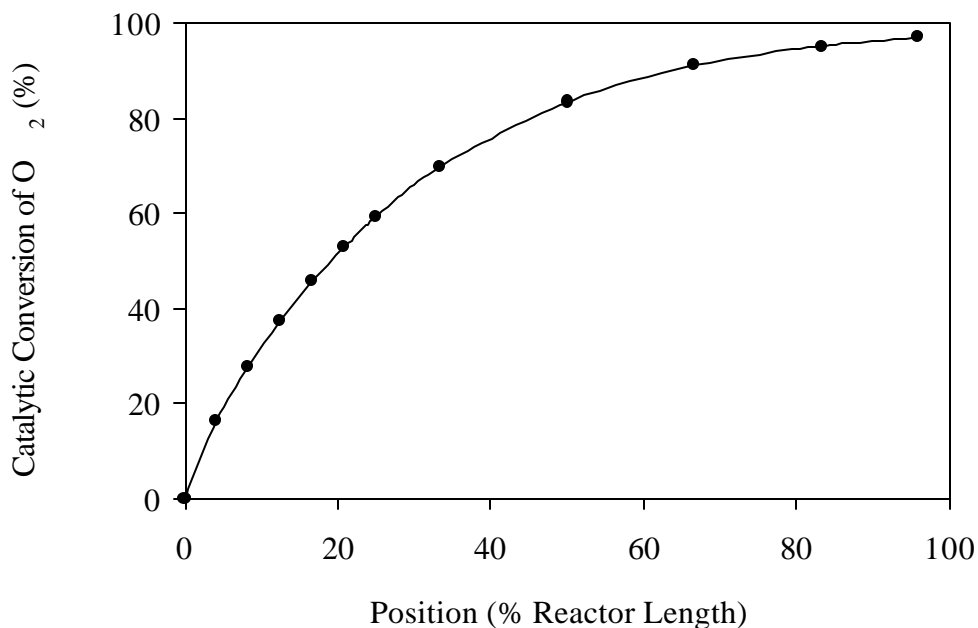


Figure 2-3. Fluent CFD predicted oxygen conversion, as a function of length through the catalytic reactor. Oxygen conversion approaches 100% at the reactor's downstream end, as desired.

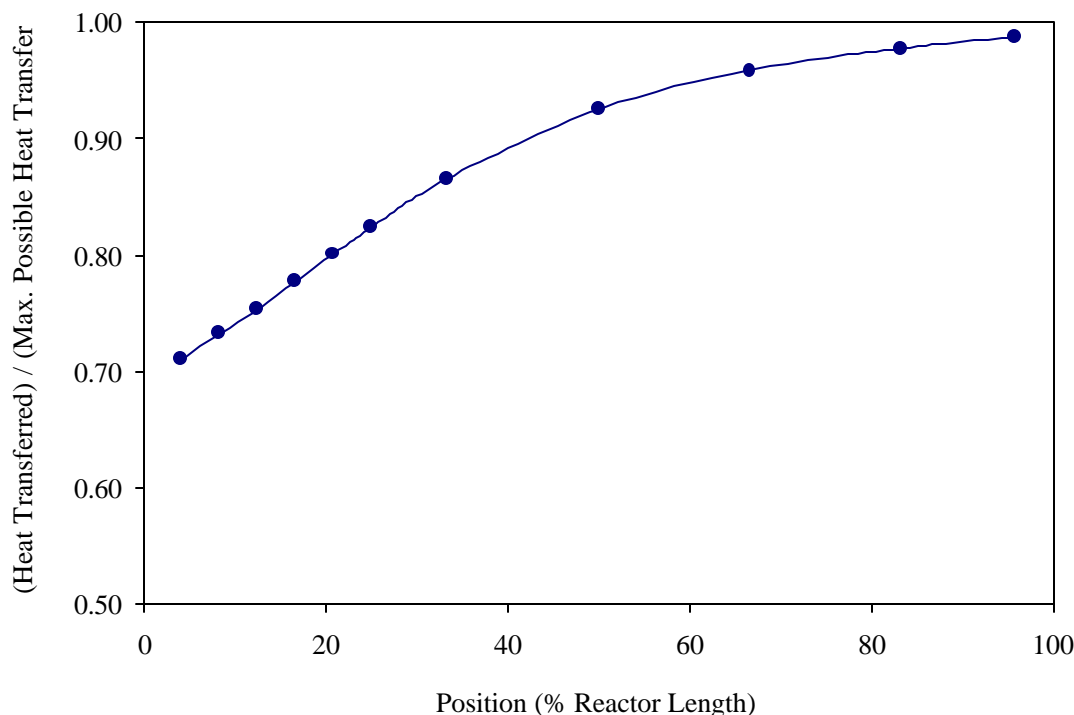


Figure 2-4. *Fluent CFD predicted heat transfer within catalytic reactor, from reacting fuel-rich mixture to cooling air stream. Maximum possible heat transfer means that the reacting stream and the cooling stream reach thermal equilibrium.*

Heat transfer, as plotted in Figure 2-4, refers to transfer of heat away from the reacting fuel-rich stream in direct contact with the catalyst and into the catalyst cooling air stream. The maximum possible heat transfer is that which brings the two streams into thermal equilibrium (equal temperature) following complete consumption of all oxygen in the fuel-rich stream. Figure 2-4 plots heat transfer normalized by the maximum possible heat transfer, and shows that PCI's reactor is effective both in releasing heat and in transferring heat to the cooling stream, thus moderating catalyst temperature and allowing considerable heat release to occur in the catalyst.

Finally, the Chemkin software package for calculation of detailed chemical reaction mechanisms was used to predict NO_x emissions from the device. For these calculations, the GRI 3.0 gas-phase reaction mechanism data were used. The calculations were performed for a 0.25 ms residence time Perfectly-Stirred Reactor (PSR), followed by a Plug Flow Reactor (PFR) of 2 ms residence time. Thus the model is zero-dimensional in space, but captures detailed chemical kinetics for reaction and NO_x formation.

PCI's simulated Tampa Electric syngas composition (20% H₂, 20% CO, 10% CO₂, and 50% N₂) was assumed to react under fuel-rich conditions on the catalyst, and to transfer heat to the cooling gas stream until thermal and chemical equilibrium were reached. The resulting output

streams were used as input to the Chemkin PSR/PFR model, and NO_x emissions were calculated for a range of flame temperatures, as shown in Figure 2-5 below. As shown, NO_x emissions are predicted to be less than 3 ppm for flame temperatures up to about 2950 F, under the 2 ms PFR assumption of the model used.

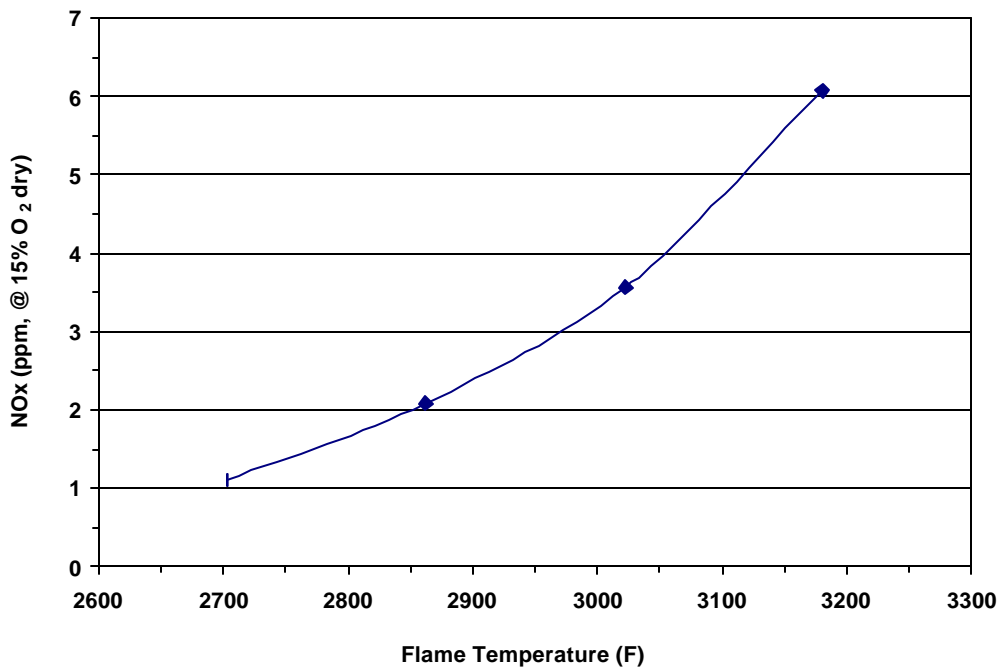


Figure 2-5. NO_x prediction as a function of flame temperature, for fuel-lean combustion downstream of PCI's RCL catalytic reactor. Predictions obtained using Chemkin's PSR/PFR model with the GRI 3.0 detailed chemical reaction mechanisms. Input to the PSR/PFR model was based on reaction of simulated Tampa Electric syngas to chemical and thermal equilibrium within PCI's RCL reactor.

3. High-Pressure (10 atm) Test Hardware and Experimental Setup

A sub-scale catalytic reactor for high-pressure testing with syngas fuel was fabricated at PCI, and is shown prior to final assembly in the photograph in Figure 3-1 above. The reactor housing is the long piece shown in Figure 3-1. Flow is from top-right to bottom-left in the photograph. During assembly an injector for syngas fuel is fitted at the upstream end of the reactor, where fuel and air mix to provide a fuel-rich fuel/air mixture to the catalyst. The large flange-like piece shown in the photograph contains the fuel plenum, and syngas fuel is delivered through the needle-like injectors shown.

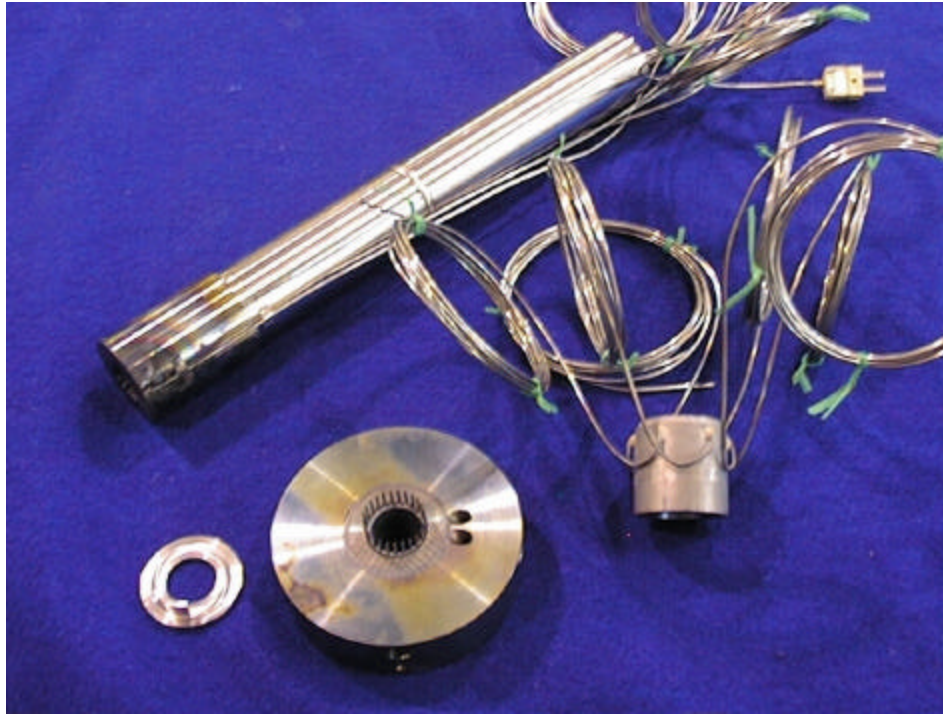


Figure 3-1. Photograph of sub-scale catalytic reactor for syngas combustion.

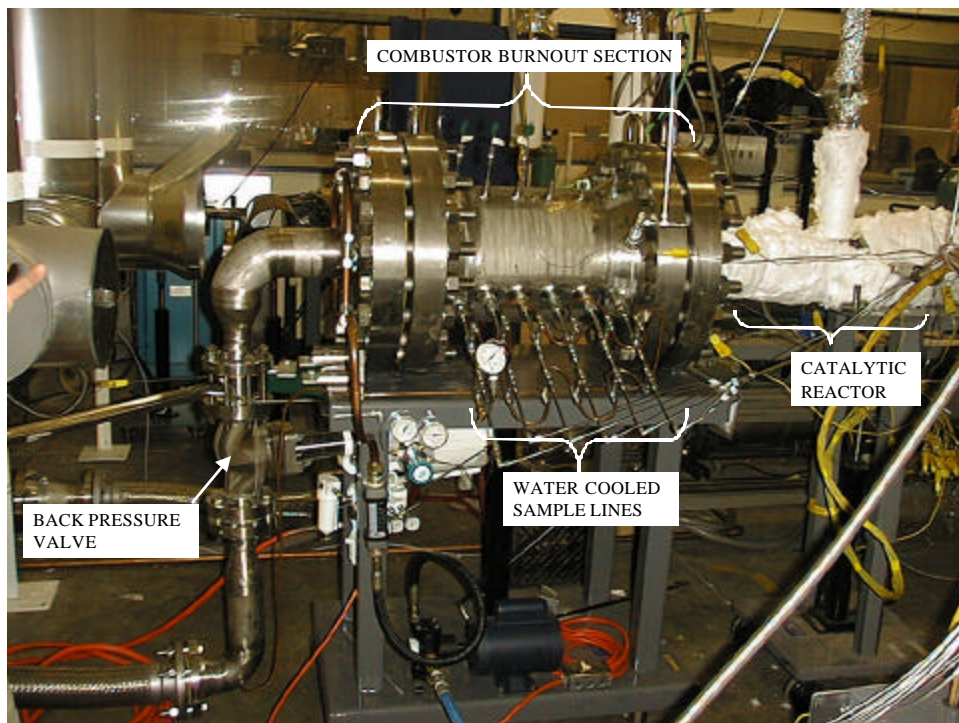


Figure 3-2. Photograph of PCI's 10 atm sub-scale combustor rig for syngas combustion.

The reactor is instrumented with thermocouples to measure catalyst and housing temperatures, flush-static pressure ports to measure reactor pressures, and gas sample extraction ports to measure gas composition entering and exiting the reactor. These instrumentation lines are coiled and visible in the photograph.

For high-pressure testing, the catalytic reactor of Figure 3-1 is inserted into the combustion test rig shown in Figure 3-2 above. Again, flow is from left to right, and the reactor is inserted at the right-hand-side of Figure 3-2. Two independently controllable air supplies are provided (both heated and at high pressure): the larger air supply (entering from the right in Figure 3-2) provides catalyst cooling air, which becomes primary zone combustion air in the gas-phase combustor; and the smaller air supply (entering from the vertical pipe at the top-right of Figure 3-2) provides air to the fuel-rich fuel/air mixture. Two fuel heaters for syngas fuel are also provided (but not shown in this photograph): one heater heats N_2 diluent just before it is mixed with fuel; the second heater heats all other fuel components and CO_2 .

Downstream of the reactor, the catalytically reacted gases and the catalyst cooling air burn in the high-pressure combustor section labeled in Figure 3-2. Here, gas-phase combustion completes the burnout of fuel within a 2-inch inside-diameter ceramic combustor liner. The combustor burnout section is instrumented with 6 type-S thermocouples to measure flame temperatures axially along the combustor liner at 3-inch increments, and 6 gas sample extraction ports (one at each axial thermocouple location). A hydrogen torch is used to ignite gas-phase combustion. This torch remains on during rig stabilization (to ensure safe burnout of all fuel prior to the rig exhaust, even if the catalytic reactor is not yet lit off), but is turned off prior to obtaining steady-state data.

High-pressure air is supplied to the rig from PCI's compressors, which can deliver 0.12 pps air at about 145 psia into the rig. At this flow rate, the rig inlet air can be heated to 500 C. Fuel and diluent are supplied from bottles or Dewar flasks at high pressure, and are pressure regulated to the proper delivery pressure to the rig. All flows (air, fuel, diluent) are metered with electronic mass flow controllers. Each fuel component is separately metered and then mixed with the other components. For the current tests, five fuel components can be introduced: H_2 , CO , CH_4 , CO_2 , and N_2 .

4. Basis for High-Pressure Test Conditions

For the high-pressure sub-scale tests, "baseline" operating conditions are based on the IGCC plant at Tampa Electric's Polk Power Station. The Tampa Polk plant operates a GE 107FA combined cycle system on syngas generated from a Texaco oxygen-blown coal gasifier. Nitrogen injection reduces the effective heating value of the fuel, for NO_x control.

At the Tampa Polk plant, the syngas composition entering the combustor is shown in the first row (Row 1) of Table 4-1 below, as published in DOE's Clean Coal Technology Topical Report Number 19, "Tampa Electric Integrated Gasification Combined-Cycle Project, An Update" July 2000. Row 1 shows the composition following syngas cleanup, but before mixing with injected nitrogen in the combustor. Row 1 also shows the Lower Heating Value (LHV) of this undiluted fuel. Row 2 of Table 4-1 shows the effective syngas composition following mixing with injected

nitrogen in the combustor (assuming that fuel and nitrogen mix prior to mixing with combustion air). Row 2 also shows an "Equivalent" Lower Heating Value for this diluted fuel. The Row 2 "Equivalent" Lower Heating Value was obtained from GE Report number GER-4207 ("GE IGCC Technology and Experience with Advanced Gas Turbines"), and the fuel composition in Row 2 was calculated based on dilution of the Row 1 fuel to this heating value. Note that wet sulfur scrubbing removes virtually all ammonia from the syngas prior to its entering the turbine.

Table 4-1. *Syngas composition at Tampa Electric Polk Power Station.*

Row Number	Nitrogen Dilution	H ₂ (%)	CO (%)	CH ₄ (%)	CO ₂ (%)	N ₂ +Ar (%)	H ₂ O (%)	LHV or Equivalent LHV
1	no	38.3	42.7	0.1	14.4	4.2	0.3	240 Btu/ft ³
2	yes	19.2	21.4	0	7.2	52	0.2	120 Btu/ft ³

Engine operating conditions for syngas fuel are not published. However, natural gas operating conditions can be used as a starting point to approximately calculate engine operating conditions. GE's 7FA engine conditions are tabulated in Table 4-2 for baseload operation on natural gas (from GE pamphlet: "Gas Turbine and Combined Cycle Products" available at www.gepower.com/corporate/en_us/assets/gasturbines_heavy/prod/pdf/gasturbine_2002.pdf).

Table 4-2. *Baseload operating conditions for 7FA engine (natural gas, simple-cycle operation).*

Engine	Output (MW)	Heat Rate (kJ/kWh)	Pressure Ratio	Mass Flow (pps)	Exhaust Temp (F)	Number of Combustors
GE 7FA	171.7	9936 (36% eff)	15.5:1	952	1116	14

For the 7FA engine, compressor discharge temperature (combustor inlet temperature) will be about 745 F on a standard day (59 F ambient) at 15.5 pressure ratio, assuming $\gamma_{\text{air}} \sim 1.4$ and 90% efficiency for the compressor. These values are for natural gas operation, and represent an approximate condition for syngas operation (since mass flow and pressure drop through the turbine change somewhat for syngas operation).

Table 4-3. *Operating data for Tampa Polk plant, from DOE's Clean Coal Technology Topical Report Number 19, July 2000 "Tampa Electric IGCC Project, An Update."*

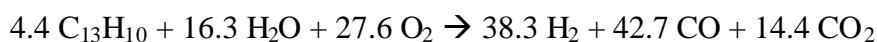
GE 7FA Power Output	Coal Feed to Gasifier	Carbon Content of Coal (Typical Analysis)	Hydrogen Content of Coal (Typical Analysis)	Oxygen Feed to Gasifier	Nitrogen Feed to Gas Turbine
192 MW (100%)	2,200 tons/day	73.76%	4.72%	2,171 tons/day	5,600 tons/day

Also, for syngas operation turbine rotor inlet temperature is lower than during natural gas operation. For example, GE Report number GER-4207 discusses NO_x emissions for a baseload

combustor exit temperature of 2550 F using syngas fuel, which is about 150 F less than the nominal 2700 F baseload combustor exit temperature for natural gas fuel (2420 F TRIT plus 280 F temperature drop across the first-stage nozzle, as published by GE). Also note that combustor airflow is affected because some compressor air is extracted for the air separation unit (ASU).

"Baseline" fuel and air flows (for the Tampa Polk plant's 7FA engine) can be calculated from data provided by DOE's publication (Clean Coal Technology Topical Report Number 19, "Tampa Electric IGCC Project, An Update" July 2000). Table 4-3 lists the relevant data.

For the carbon/hydrogen ratio listed in Table 4-3, and for the syngas composition listed in Row 1 of Table 4-1, the 2171 tons per day oxygen feed makes 2090 ft³/s syngas, or about 150 ft³/s of syngas to each of the engine's 14 combustors. This calculation is based on the overall (average) reaction



At the engine's combustors, about 5600 tons/day of N₂ is added, to bring the equivalent lower heating value of the fuel to about 120 Btu/ft³, giving the syngas composition listed in Row 2 of Table 4-1. To achieve the 2550 F burner outlet temperature, this diluted syngas is then burned with about 48 pps air in each of the engine's 14 combustors.

Table 4-4. *Calculated (approximate) single combustor conditions for 7FA engine (syngas fuel).*

Pressure	Combustor Inlet Temperature	Combustor Outlet Temperature	Combustor Airflow	Nitrogen Diluent Flow	Fuel Flow (Undiluted Syngas)
15.5 atm	745 F	2550 F	48 pps	150 ft ³ /s	150 ft ³ /s

Based on the above discussions, baseload combustor operating conditions are listed in Table 4-4, for one combustor (of fourteen total) at the Tampa Polk site. The listed conditions are calculated and approximate, but are useful in determining appropriate test conditions for PCI's sub-scale syngas catalytic combustor.

Table 4-5. *Nominal baseload sub-scale operating conditions at PCI (10 atm pressure).*

Pressure	Combustor Inlet Temperature (Air & Fuel)	Combustor Outlet Temperature	Combustor Airflow	Nitrogen Diluent Flow	Fuel Flow (Undiluted Syngas)
10 atm	750 F	2550 F	0.048 pps	0.15 ft ³ /s	0.15 ft ³ /s

For sub-scale testing at PCI, a catalytic reactor was fabricated having a total cross-sectional area of about 0.37 in², including both flow area for the fuel-rich fuel/air mixture (in direct contact with the catalyst) and flow area for catalyst cooling air (in thermal contact with the catalyst). Also, PCI's high-pressure rig is capable of only 10 atm operation (not 15.5 atm). Thus, for PCI's design injection velocities the flow rates given in Table 4-4 drop by about a factor of 1000. On

this basis, nominal baseload operating conditions for the sub-scale reactor at PCI are listed in Table 4-5.

Finally, for simplicity the "baseline" syngas fuel composition shown in Row 2 of Table 4-1 is approximated for these tests with the following composition:

Table 4-6. *Simplified baseline syngas composition used for high-pressure tests.*

H ₂	CO	CO ₂	N ₂	LHV
20%	20%	10%	50%	117 Btu/ft ³

5. High-Pressure Sub-Scale Test Results for Syngas Fuel

Test Objectives

The primary goal of the Phase I sub-scale tests was to evaluate emissions performance of PCI's catalytic combustion system with syngas fuel. Thus, the primary objectives listed below relate to measurement of the downstream combustor output:

Primary Objectives -- Catalytic combustor (final burnout) performance for syngas fuel:

1. Characterize combustor emissions (NO_x, CO, UHC) and lean blowout (LBO) at baseline conditions. Vary fuel flow to establish low-emissions turndown range (low NO_x and low CO). Use "baseline" syngas fuel composition, "baseline" reactor configuration (fixed percentage of air to fuel-rich fuel/air mixture), and "baseline" (baseload) inlet air conditions (constant pressure, air flow, temperature).
2. Characterize combustor performance (emissions, LBO) for non-"baseline" syngas fuel compositions. In particular, keep constant H₂/CO ratio but vary Btu content. For each fuel composition tested, vary fuel flow to establish low-emissions turndown range.
3. Characterize effect of pressure on NO_x emissions, to help extrapolation/prediction of NO_x emissions at full 15 atm pressure.
4. Characterize effect of catalytic reactor parameters on NO_x emissions. For example, vary reactor throughput (velocity).

Prior to this project PCI had not tested its catalytic reactor with syngas fuels. Therefore, a secondary objective (and the first milestone in preparing for emissions tests) was to evaluate catalyst and reactor performance using syngas fuel:

Secondary Objectives -- Catalytic reactor (catalyst stage only) performance for syngas fuel:

1. Characterize catalyst operating temperatures.
2. Characterize fuel and oxygen conversion in the catalytic reactor, at 10 atm pressure.

3. Characterize effective areas (pressure drops) for the catalytic reactor.

Emissions Performance

Emissions measurements reported here were obtained from the gas sample port located 15 inches downstream of the catalyst, corresponding to 50 ms residence time. This represents the maximum residence time expected in a low-emissions gas turbine combustor, and therefore also represents the maximum expected NO_x emissions for a given operating condition. All emissions reported in ppm are corrected to 15% excess oxygen, dry.

All measurements were made with a combustor inlet air temperature of 750 F and a syngas fuel temperature of 570 F. Adiabatic flame temperatures were calculated based on fuel/air ratio as measured by the emissions analyzers (i.e. from gas samples extracted at the 15-inch gas sample probe location).

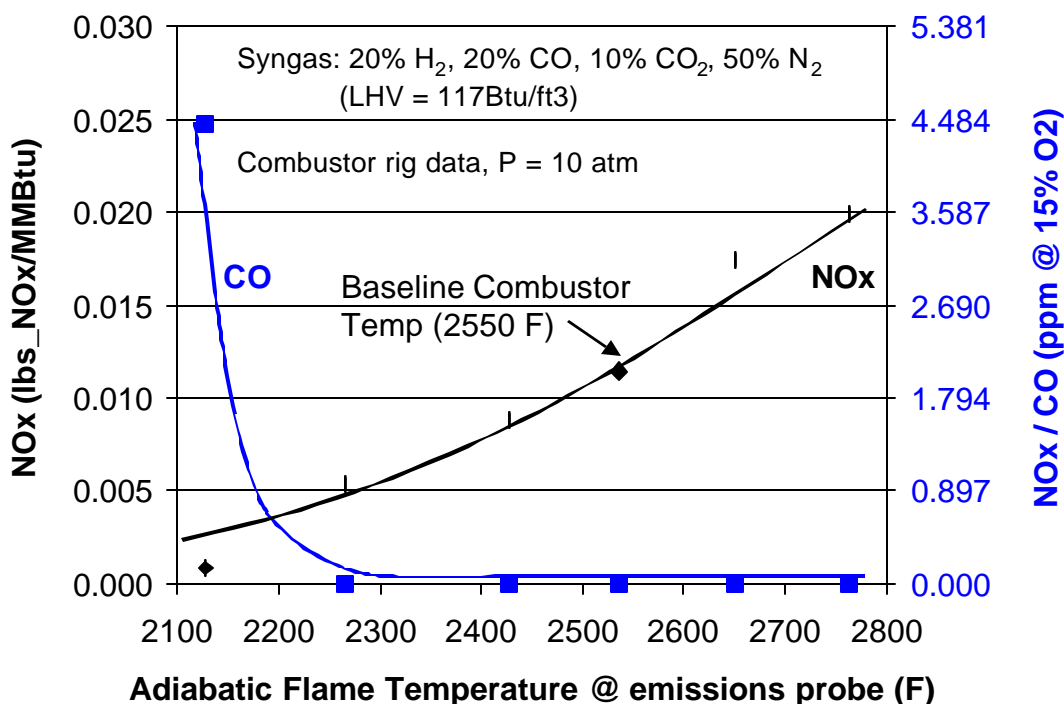


Figure 5-1. Measured NO_x and CO emissions in PCI's sub-scale rig at 10 atm pressure, as a function of adiabatic flame temperature at the emissions probe. For this data, the syngas fuel's Lower Heating Value (LHV) was 117 Btu/ft³. For 2550 F baseline flame temperature, NO_x emissions were 2.0 ppm at 15% excess oxygen, or 0.011 lbs/MMBtu.

Figure 5-1 plots measured NO_x and CO emissions as a function of adiabatic flame temperature at 10 atm pressure for a “baseline” syngas composition of 20% H₂, 20% CO, 10% CO₂, and 50% N₂, giving a Lower Heating Value (LHV) of 117 Btu/ft³. With this fuel composition, NO_x emissions were 0.011 lbs/MMBtu at the 2550 F flame temperature data point corresponding to

the “baseline” IGCC firing temperature and representing operation at 100% load. Also note that for this syngas fuel composition 0.011 lbs/MMBtu is equivalent to 2.0 ppm NOx.

As the fuel/air ratio was decreased CO emissions remained near zero for flame temperatures greater than about 2250 F, permitting a 300 F turndown in flame temperature from the 2550 F baseline point, and allowing ultra low emissions operation over a wide range of loads.

These results – CO near zero, and NOx equal to or less than 0.011 lbs/MMBtu (2.0 ppm) for full load and below – easily met our 0.03 lbs/MMBtu NOx goal for this project, and are very near our 0.01 lbs/MMBtu NOx target.

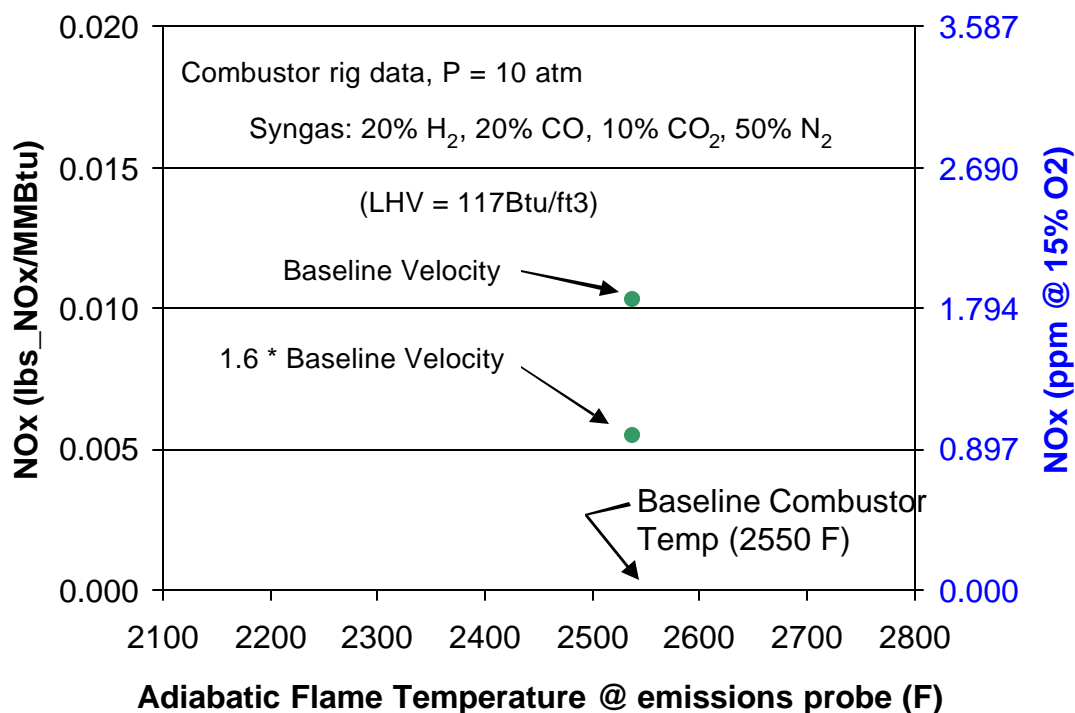


Figure 5-2. Measured NOx emissions in PCI’s sub-scale rig at two different velocities, for 2550 F baseline flame temperature. For both data points pressure is 5 atm, and the baseline syngas composition was used (LHV = 117 Btu/ft³). As shown, NOx emissions well below 0.01 lbs/MMBtu (less than 2 ppm at 15% O₂) were achieved for the higher velocity condition.

In fact, NOx emissions below the 0.01 lbs/MMBtu target were achieved during parametric testing, as shown in Figure 5-2. Here, rig pressure was reduced to 5 atm to allow operation at increased velocity without exceeding PCI’s air supply capability. Two different cases were tested to determine the effect of velocity on NOx emissions. The first 5 atm case, labeled “baseline velocity” in Figure 5-2 used the same reactor velocity as used during 10 atm testing, and gave similar NOx emissions results (0.010 lbs/MMBtu) as the 10 atm case. The second 5 atm case showed a significant reduction in NOx emissions with increased velocity. At a velocity 1.6 times higher than baseline, NOx emissions dropped to 0.005 lbs/MMBtu or 1.0 ppm, well

below our project target of 0.01 lbs/MMBtu. CO emissions were near zero for both data points shown in Figure 5-2.

In another parametric test, syngas composition was varied to determine the effect of fuel heating value on NO_x emissions. NO_x emissions for three syngas compositions are shown in Figure 5-3. Note that the right-hand vertical axis in Figure 5-3 (NO_x values in ppm) is only applicable to the baseline syngas composition, as marked. For the fuel composition with higher heating value than baseline, NO_x emissions in ppm are slightly higher than shown (0.037 lbs/MMBtu is equivalent to 7.6 ppm); and for the fuel with lower heating value NO_x emissions in ppm are slightly lower than shown (0.011 lbs/MMBtu is equivalent to 1.6 ppm).

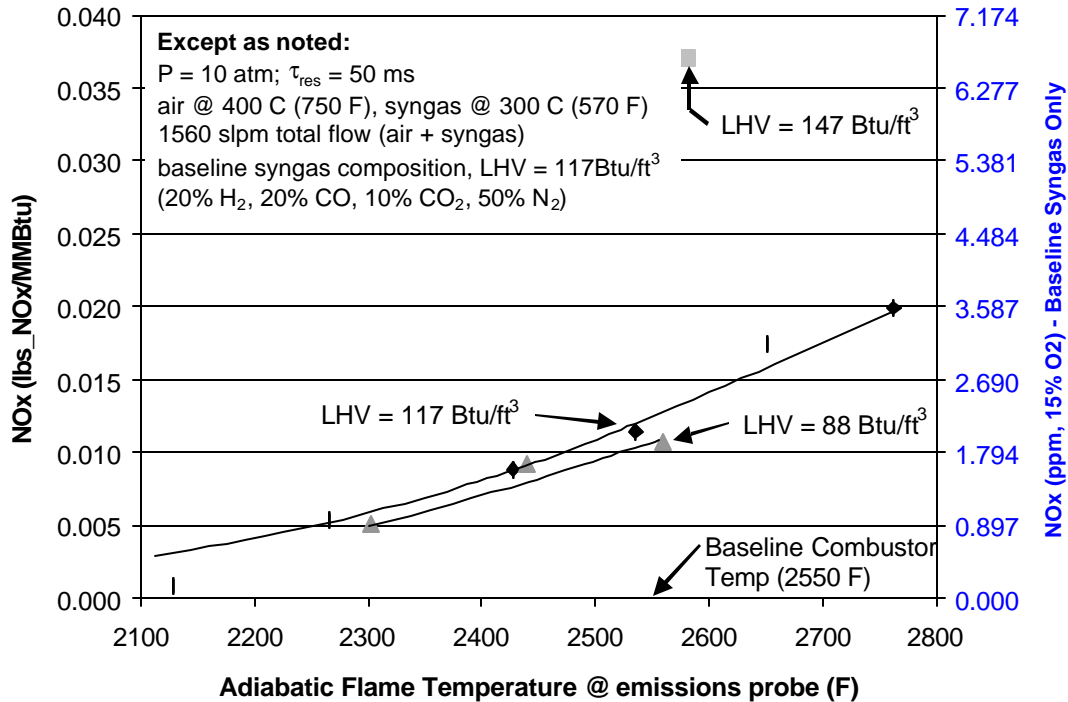


Figure 5-3. Measured NO_x emissions in PCI's sub-scale rig for three different syngas compositions having Lower Heating Values (LHVs) of 88, 117, and 147 Btu/ft³.

Table 5-1. Syngas compositions for data shown in Figure 5-3, arranged by heating value.

H ₂	CO	CO ₂	N ₂	LHV
15%	15%	10%	60%	88 Btu/ft ³
20%	20%	10%	50%	117 Btu/ft ³
25%	25%	10%	40%	147 Btu/ft ³

As shown in Figure 5-3, reducing the syngas heating value by adding more nitrogen diluent decreased NO_x emissions slightly, to 1.0 ppm. Conversely, increasing the heating value by reducing nitrogen diluent increased NO_x emissions somewhat, to 7.6 ppm. It is also worth noting that catalytic combustion allows stable operation with low emissions for the very low Btu syngas case (88 Btu/ft³) even at flame temperatures as low as 2300 F. CO emissions were less

than 5 ppm in all cases, and were very near zero for flame temperatures greater than 2200 F. The fuel compositions for the data shown in Figure 5-3 are listed in Table 5-1.

Performance Measures for Catalytic Reactor

Gas samples were extracted from the partially reacted fuel-rich stream at the downstream end of the catalytic reactor, just prior to mixing with cooling air for final combustion. The samples were analyzed by gas chromatograph, to provide a measure of the concentrations of the major species H_2 , CO, O_2 , N_2 , and CO_2 . From this data, conversions of the reactant species were calculated. At 10 atm pressure and baseline operating conditions, O_2 conversion was 95%, H_2 conversion was 35%, and CO conversion was 25%. The 95% O_2 conversion indicates that PCI's reactor, as designed for syngas fuel operation, has sufficient catalyst surface area to provide nearly complete conversion at 10 atm pressure even with high volume syngas flow. The comparable 25% and 35% CO and H_2 conversions, respectively, indicate that the reactor does not exhibit a strong bias toward preferential reaction of H_2 at the conditions tested.

Pressure Drop and Sizing Requirements

PCI's high-pressure rig allows for two separate air supplies: one supply feeds the fuel-rich stream contacting the active catalyst, and the other supply feeds the catalyst cooling air stream which provides final combustion air for the downstream combustion zone. The two supplies can operate at different pressures, and this allows for independent and flexible control of the two streams during testing, regardless of pressure drop through the catalyst and combustion system.

Pressure drop was measured across the fuel-rich flow path contacting the active catalyst, and was also measured across the catalyst cooling flow path. In both cases, pressure drop was measured from upstream of the catalytic reactor to downstream of final gas-phase combustion. Note that the majority of combustion air passes through the catalyst cooling flow path, and that this is therefore the more limiting parameter in ultimately determining catalyst size requirements and engine performance. The balance of the combustion air mixes with all of the syngas fuel upstream of the catalyst and then contacts the active catalyst to partially react before mixing with final combustion air from the catalyst cooling air path for final burnout.

At the 10 atm baseline operating conditions, pressure drop across the catalyst cooling flow path was approximately 2%, well within the allowable pressure loss for most gas turbine combustion systems. Pressure drop across the fuel-rich flow path contacting the active catalyst was significantly higher, however, and was measured at about 11% of combustor inlet pressure. This high pressure drop is due to the high volume of flow that results when using high-volume (low-Btu) syngas. To address this high-pressure drop issue, PCI has designed an improved catalytic reactor for syngas fuels which provides greater open area for the fuel-rich flow path contacting the active catalyst, with only a small increase in overall reactor size. This new reactor will be evaluated in detail during Phase II of the project, as described further in Section 6 of this report.

Since the 2% pressure drop across the catalyst cooling flow path is the more limiting parameter for catalyst sizing, calculations of expected catalyst size were made for the 2% pressure drop case at the combustor conditions given in Table 4-4, approximately representing operation of a

single syngas combustor (out of fourteen total) in Tampa Electric's 7FA gas turbine engine. Table 5-2 lists the combustor diameter required to accommodate PCI's syngas catalytic reactor for pressure drops of 2%, 3%, and 5%, based on the sub-scale data. For all cases listed the required combustor diameter is reasonable for the engine application.

Table 5-2. Combustor size requirements as a function of catalyst pressure drop.

Catalyst Pressure Loss (ΔP)	Combustor Diameter
2%	18 inches
3%	16 inches
5%	14 inches

6. Phase I Summary and Recommendations

Phase I milestones and corresponding accomplishments are listed here, showing that the milestones were met successfully:

- **Milestone 1: Successful high-pressure catalytic combustion of syngas.** Tests were performed in PCI's sub-scale combustion rig at 10 atm pressure with heated syngas over the planned range of operating conditions. Catalyst performance measures showed good operation (catalyst temperatures, catalytic conversion), confirming that PCI's basic reactor design, catalysts, and substrate metallurgy are applicable to syngas operation.
- **Milestone 2: Successfully achieved $\text{NO}_x = 0.011 \text{ lbs/MMBtu}$ at 10 atm pressure** (corresponding to 2.0 ppm NO_x corrected to 15% O_2 dry) with near-zero CO emissions, easily meeting our project goal of $< 0.03 \text{ lbs/MMBtu NO}_x$. These emissions levels were achieved at scaled (10 atm, sub-scale) baseload conditions corresponding to Tampa Electric's Polk Power Station operation on 100% syngas (no co-firing of natural gas).

This project has been directed toward DOE's goals of developing low-emissions coal-based power systems. Specifically, the technology to be developed is expected to meet DOE's Vision 21 target of NO_x emissions $< 0.01 \text{ lbs/MMBtu}$ ($< 3 \text{ ppm @ 15\% O}_2$) for coal-derived fuels. The technology offers these low emissions without the cost of exhaust after-treatment, with high efficiency (avoidance of after-treatment losses), and with catalytically stabilized combustion which extends the lower Btu limit for syngas operation.

Based on the successful sub-scale test results to date, and on OEM interest in a detailed study for engine application and commercial potential, PCI recommends that DOE provide funds to allow continued technology development for catalytic combustion of syngas and high-hydrogen fuels, and for interactive work with gas turbine OEMs to evaluate product potential and bring the technology closer to commercial readiness.

7. Assessment of Potential Success and Feasibility for IGCC

Technical results from this program to date were highly successful. These support an expectation that the proposed combustion system is feasible for IGCC application and offers key

benefits in terms of expanded capability, lower emissions, and reduced cost such that the technology offers to advance commercialization potential of IGCC both in terms of total volume and timing.

High pressure catalytic combustion of syngas was successfully achieved at subscale, with good catalyst performance and confirming that PCI's basic reactor design, catalysts and substrate metallurgy are applicable to syngas. Results to date support the following expectations for the RCL catalytic combustor technology:

1. Ultra-low NO_x emissions
 - Targeted at < 0.03 lbs/MM BTU and a goal of 0.01, vs current industry standard at approximately 0.10 lb/MM BTU
 - Phase I subscale results at 10 atm pressure of slightly above 0.01 lbs/MM BTU at the baseline combustor temperature, or the equivalent of around 2 ppm NO_x
 - The 0.03 lbs/MM BTU target was met even at much higher combustor temperatures, e.g. 0.02 lb/MM BTU was achieved at +200F above baseline.
 - The ability to meet DOE emissions objectives without post-combustion control using SCR, with large capital and operating savings.
 - The potential for achieving higher temperature operation at low NO_x in syngas turbines, should system objectives and capabilities support this objective.
 - The ability to burn syngas with low NO_x emissions with reduced nitrogen dilution requirement.
2. Ability to burn lower BTU gas than conventional combustion
 - The lowest BTU gas tested (LHV 88 BTU/ft³) also was operable across its tested temperature range, with slightly lower NO_x than the baseline case.
 - Broadened applicability for IGCC where processes that now require supplemental fueling to raise BTU content can either avoid such cost or require less of it. This may also be an indication of the ability to burn less reactive mixtures.
3. Operability and size were consistent with fitting to current engines.
4. Life is expected to be similar to the current target for the natural gas-fired application of the RCL technology (25,000).
5. Potential for reduced-NO_x operation with other hydrogen-containing fuels, including process industry byproducts (e.g. refinery gas), and hydrogen itself.

The technology remains at a development stage, with issues identified to be addressed in the proposal Phase II program. These are discussed in the Phase II program proposal.

The technology offers to avoid the need for SCR (and related additional sulfur cleanup) to meet DOE emissions goals, providing cost savings as follows:

- Capital cost savings of \$20/kW SCR and \$50/kW for related sulfur cleanup. This is a significant fraction of the estimated total capital cost of IGCC power.
- Operating cost savings of 1-2 mills, also a significant savings. These arise from avoiding

the operating costs of SCR, improved efficiency, improved component life, and the potential for NO_x trading earnings.

- Avoided ammonia slip

For example, for an IGCC gas turbine supplying 190 MW, we estimate capital savings at approximately \$14 million in capital and annual operating savings at \$2 to \$3.5 million.

Also, IGCC technology faces a certain degree of market entry challenge in terms of the very limited number of actual gasification sites (prior to broad commercialization of large scale coal-based IGCC). The RCL technology offers to broaden the range of low BTU and high hydrogen industrial waste gas applications due to the lowered BTU capability and the lower cost achievement of low emissions. Especially relating to refinery applications or other industrial applications, there may be a number of potential applications where current emissions, clean-up costs, and/or post-combustion control footprint requirements together lead to no application where otherwise there could be a power plant.

The Phase I results were sufficiently positive that our gas turbine OEM participant is seeking to skip the scale-up to module test and instead seeking to address basic combustion design issues that relate to how the technology would fit to actual engines. In addition, the OEM is considering and at a very early stage exploring with customers the potential application to specific industry opportunities where high hydrogen content gas is available, to prepare for moving the technology past the next-stage combustor trial stage into actual specific applications development with targeted customers. In this regard, we have also attracted interest in the technology from a major oil refiner, who has assessed that this technology could provide a viable approach for it to utilize more refinery gas for gas turbine combustion, and who has offered the potential for a joint program to explore this application.

In summary, the result of our preliminary assessment is that the technology offers lower emissions, increased fuel flexibility, and reduced costs for IGCC applications. These results are leading to more rapid exploration of the technology, and offer the potential for meeting DOE emissions targets at lowered cost and applied to a broader set of industrial applications.